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Development, validation, and demonstration of HUMS technologies to detect rotorcraft mechanical faults

FAA HUMS R&D Review Meeting

13 February 2007

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Presentation Topics

1. **FAA HUMS research program overview**
   - Objectives
   - Work tasks
2. **Summary of Year 1 effort**
   - Assessment of HUMS CBM credit potential
   - Selection of rotorcraft component and CBM credit for the research program
   - Application of HUMS algorithms and methodologies
   - End-to-end CBM credit approval process
3. **Program Status**
4. **Summary**
5. **Questions**

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FAA HUMS research program overview

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Research Objectives

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The two complementary research objectives are:

1. Develop, validate and demonstrate HUMS technologies including advanced software, algorithms, and methodologies to
   (a) detect faults or component degradation before incipient failure,
   (b) predict future component degradation or fault progression, and
   (c) increase the probability of detection and reduce false alarm rate.
2. Research the validation of existing and new HUMS technologies for an example maintenance credit in accordance with the requirements of AC29-2C MG 15.

The research will focus on HUMS mechanical diagnostics

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Task Summary

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Task 1: Project planning, reporting and meetings

Task 2: Define target CBM credit, requirements, and risks — **Year 1**

- Task 2.1 – Select representative component and fault(s) for project focus based on existing engineering, operational, and O&R data
- Task 2.2 – Evaluate Failure Hazard Analysis (FHA) for selected component and fault(s)
- Task 2.3 – Define target CBM credit, requirements, risks and finalize project objectives

Task 3: Demonstrate HUMS condition indices and thresholds, and develop/mature advanced algorithms and methodologies — **Year 2-4**

Task 4: Acquire baseline and seeded fault test data — **Year 2-3**

Task 5: Establish CBM preliminary criteria for target component, fault(s), and credit — **Year 2-4**

Task 6: Develop example plans and research end-to-end CBM credit approval process in accordance with AC29-2C Sec. MG-15 — **Year 2-5**

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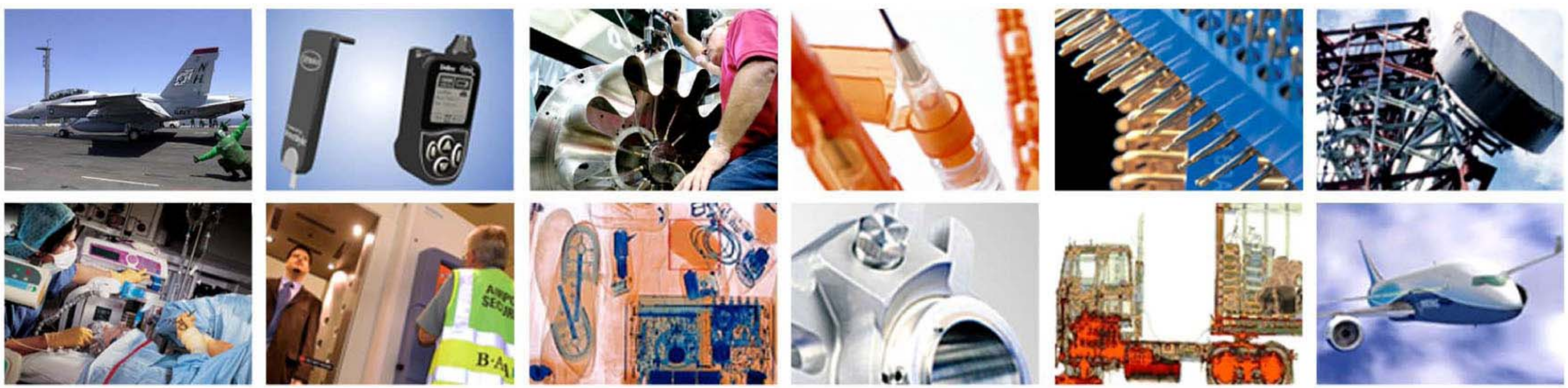
Summary of Year 1 effort (on Task 2 - a program definition task)



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Assessment of HUMS CBM credit potential

Current HUMS credit status on civil rotorcraft

The focus of this research is on mechanical diagnostics

Very limited credit has been awarded to current HUMS mechanical diagnostics functions

The only credits that have been awarded are:

- Those in which HUMS replaces an item of ground test equipment -
- and where it is possible to show directly from experience that HUMS provides the same results as an independent measuring system.

However, in-service experience does indicate the future credit potential of HUMS mechanical diagnostics.

UK examples

Limited rotor adjustments based on HUMS data from routine flights

HUMS fulfils a requirement for high speed shaft monitoring

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In-service HUMS experience illustrating the credit potential of mechanical diagnostics

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Eg 1: HUMS detection of accessory gearbox (AGB) defects on AS332L2

- There have been a number of repeat occurrences of a particular defect type within an AGB, resulting in rejections before the TBO limit is reached.
- In-service experience has demonstrated that the HUMS can reliably detect vibration characteristics associated with the defect.
- The HUMS information has been used to determine when gearboxes are rejected
- The AGBs are effectively operating 'on-condition' for this defect mode.

Eg 2: HUMS based fleet-wide health check on military CH-47D

- The break-up of a combiner transmission input bearing was detected by debris monitoring. A HUMS had been newly fitted to the aircraft, but no thresholds had yet been set.
- A failure characteristic was identified from the VHM data acquired by the HUMS, and used to screen the rest of the fleet within 12 hours.
- Again, for a single defect mode that was shown to be detectable on an in-service aircraft, the HUMS was awarded a 'one-off credit' – preventing a fleet grounding for gearbox removal and inspection for bearing failure.

In-service HUMS experience illustrating the credit potential of mechanical diagnostics

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Eg 3: HUMS based bearing servicing on Super Puma

- Rising trends in vibration energy levels on the tail drive shaft bearings of AS332L2 aircraft were found to be related to the state of the grease lubrication.
- Repeating greasing cycles created a 'saw tooth' trend, with progressive increases in vibration followed by step decreases.
- The rising HUMS vibration trends have been used to indicate when bearing re-greasing is required

Summary

- These examples from in-service experience illustrate that HUMS mechanical diagnostics do have the potential to provide CBM credits.
- They also suggest that the realization of this potential can be most straightforwardly achieved in cases where:
  - Only a limited number of specific defect modes are involved.
  - There is direct evidence from in-service experience of the ability of the HUMS mechanical diagnostics to reliably detect these defect modes.

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Selection of rotorcraft component and CBM credit for the research program

Drivetrain Components

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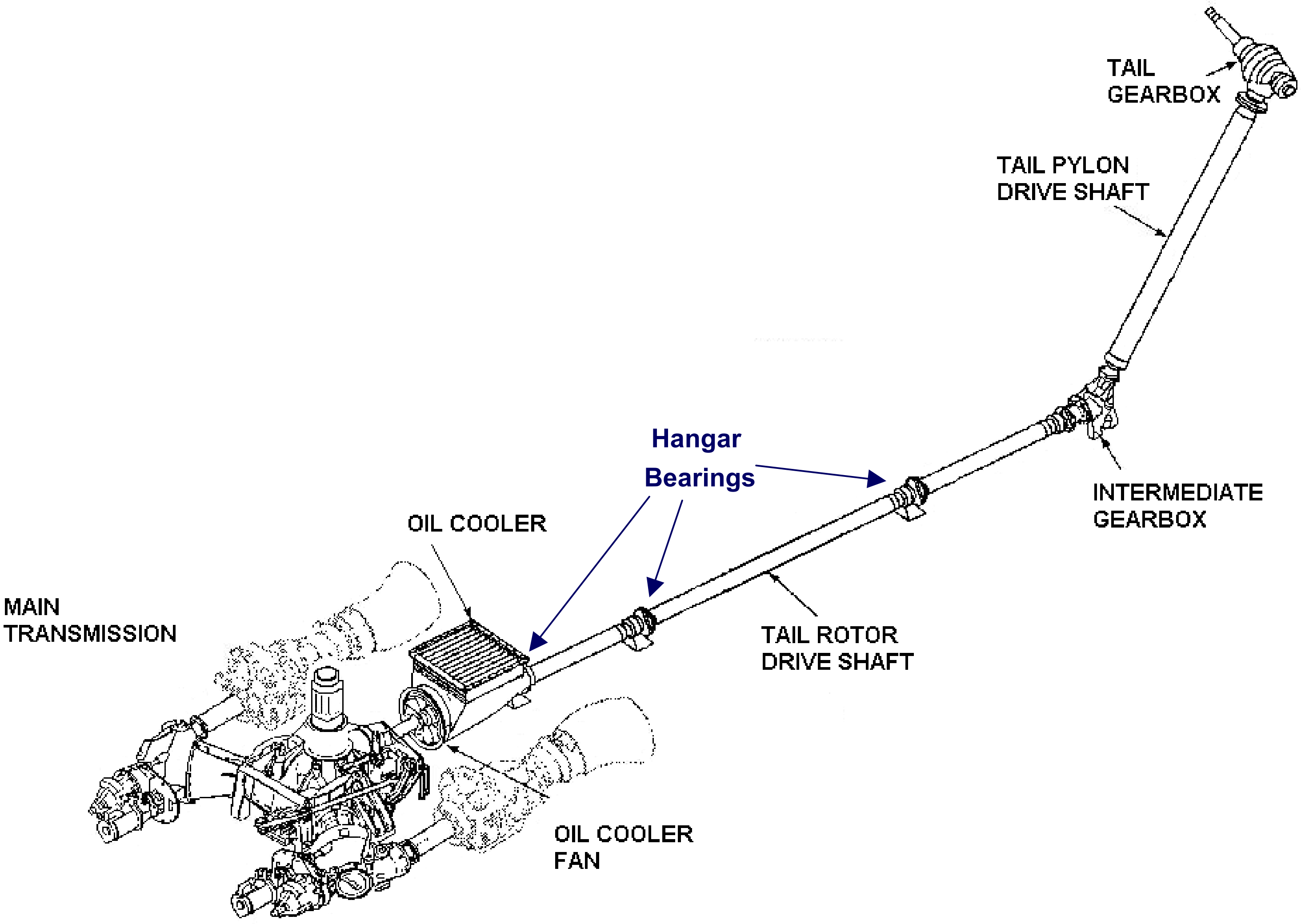

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Component and Target CBM Credit Selection Criteria

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Component History

- Unscheduled vs scheduled
- Primary MTBR or TBO drivers
- Impact on availability
- Cost of Repair

CBM Benefit

- Benefit of early detection
- Feasibility of extending TBO
- Feasibility of eliminating inspections

CBM Credit Complexity

CBM Credit Criticality

Inspectability

- Walk Around
- At-aircraft maintenance inspection
- Teardown

Detectability

- Existing HUMS sensors

Availability of Seeded Fault Test Data

Testability

Synergy with other programs

Typical Drivetrain Overhaul/Retirement Times

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Component	S-76 Aircraft			S-92 Aircraft			UH-60A/L Aircraft		
	Inspection Times(s)	Replace	TBO	Inspection Times(s)	Replace	TBO	Inspection Times(s)	Replace	TBO
Drivetrain									
MGB	100, 300, 1500		3250	50, 500, 1250		6000	700		
IGB	1500		4500	250, 1250			700		
TGB	50, 100, 500, 1500		4000	50, 250, 1250			700		
Oil Cooler Blower	25, 100, 300		3000	50, 250, 500, 1250	9000		40, 120, 700		
Oil Cooler Bearing					2500/ 5yrs			2000	
TDS Bearing Support Assembly	100		3000/ 5yrs	50, 250, 1250	2500/ 5yrs		700	2000	

Component and Target CBM Credit Selection Matrix

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Selection Criteria	Definition of Ranking	Weight	MGB	Input Module	AGB	Oil Cooler	IGB	TGB	TDS Bearing
Component History	Low (1) to high (5) impact on cost or availability	3	1	1	1	2	1	1	3
CBM Benefit	Low (1) to high (5) benefit	5	3	3	3	3	3	3	1
CBM Credit Complexity	High (1) to Moderate (5) complexity	4	1	2	3	4	3	2	N/A
CBM Credit Criticality	High (1) to low (5) critcality	5	1	4	5	3	1	1	1
Inspectability	High (1) to low (5) inspectability	5	5	5	5	5	5	5	1
Detectability	Low (1) to high (5) detectability	5	1	3	3	4	3	3	5
Availability of Seeded Fault Test Data	Low (1) to high (5) data availability	3	1	3	2	5	3	3	4
Testability	Low (1) to high (5) testability	3	1	2	2	5	3	3	5
Synergy with other programs	Low (1) to high (5) synergy	3	1	1	1	5	1	1	3
	Total Score with Weighting		66	104	110	142	96	92	85
	Total Score with Weighting (without # 7 - 9)		57	86	95	97	75	71	49
	Number of FMEA Structural & Mechanical failure modes		173	87	39	17	47	59	5
	Number of Class I failure modes		29	0	0	4	18	20	2
	Number of Class II failure modes		14	29	3	0	1	0	0

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Selected Component: oil cooler

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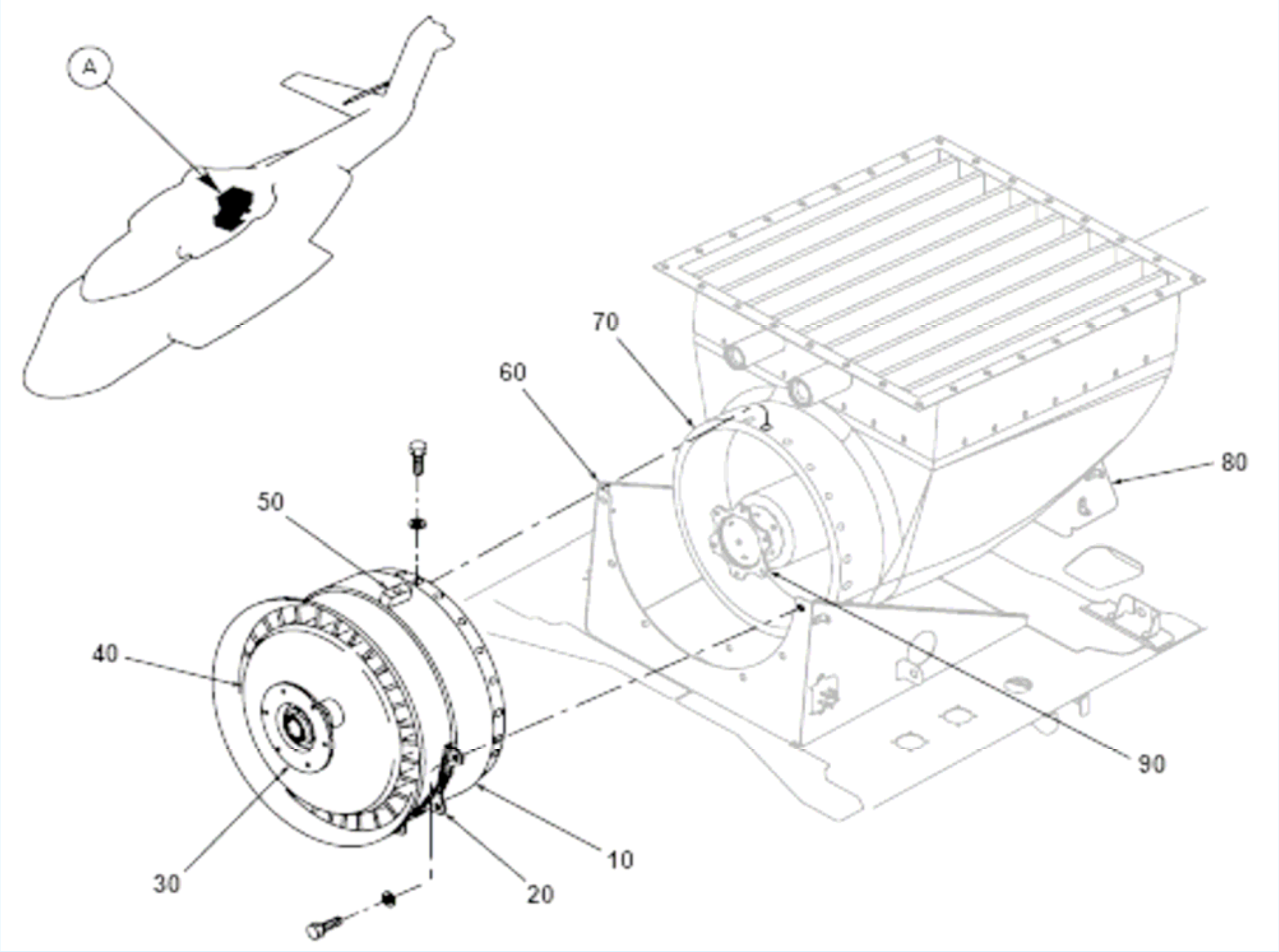
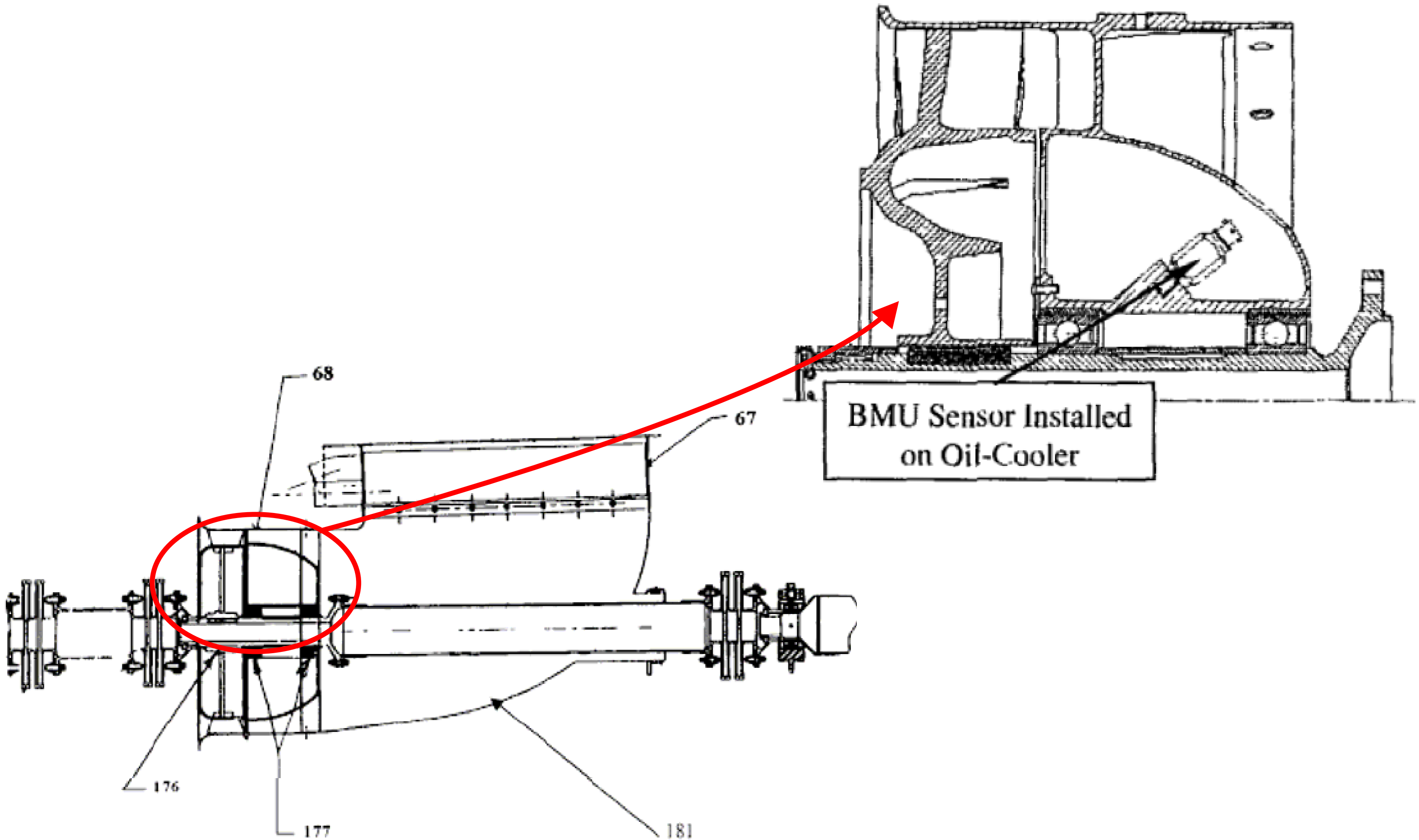


Selected Component: oil cooler



Target CBM Credit Selected

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Eliminate or extend S-92 oil cooler bearing replacement

- MTBR ~2500 Hrs → On-condition desired
- Limited number of failures modes drive TBOs
- Teardown currently required for inspection
- Good detectability with existing HUMS sensors
- Good testability
- Low credit complexity, medium criticality
- Low to medium benefit
- Significant synergy with other programs

Optional Credit -- Eliminate or extend 50-hr oil cooler inspections

Oil Cooler FMEA

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Function	Failure Mode	End Effect	Dection Methods	Compensating Provisions	Failure Class	2500 TBO	50 Hr
Oil Cooler Drive Shaft	Spline Wear Shaft Fracture Flange Fracture	Abrupt change in aircraft bearing (yaw) and loss of tail rotor thrust	Loss of yaw.	Part is full-scale fatigue tested, with flaws, to establish fatigue life Spline design is based on 45% of teeth carrying the load.	I Catastrophic		X
MGB oil cooler fan	Fan Integrity	Deterioration of oil cooler mount. Increased vibration and movement between fan house and support bracket. Loss of fan and cooling air leading to increased MGB oil temp Wear of fan blades possibly leading to failure of impeller.	Inspection. Noise and vibration. Oil temperature.	Multiple, redundant fasteners HUMS/BMS vibration monitoring Inspection.	IV Minor III Major		X
MGB oil cooler fan bearing	Ball wear/spalling. Cage fracture.	Excessive oil cooler vibrations.	Vibration.	HUMS/BMS. Inspections. Redundant component.	IV Minor III Major	X	X
MGB oil cooler duct	Duct fracture	MGB oil temperature may increase.	MGB oil temp	Inspection.	IV Minor		
MGB oil cooler heat exchanger	Cracked core	Return to platform or shore.	MGB oil pressure.	Oil cooler bypass system.	III Major		
	Temp bypass valve fails to open	MGB oil temp increases beyond acceptable limits. Possible damage of core.	MGB oil temp	Oil cooler bypass demo shows MGB can run > 3 hours without cooling.	IV Minor III Major		
MGB oil cooler system plumbing	Leak in hoses, plumbing, or radiator.	Loss of oil pressure. Activation of bypass valve.	MGB oil pressure.	Oil cooler bypass system. Inspection.	II Hazardous		
MGB oil cooler by-pass system	Solenoid failures. Faulty position switch. Internal valve leak. Cut o-ring. Cracked Tube. Cracked housing.	Loss of oil pressure leading to land immediately situation.	MGB oil pressure. MGB oil temp.	Oil cooler bypass demo shows MGB can run > 3 hours without cooling. Pre-flight check of system to ensure proper operation. Leak is detecatable by declining oil pressure. Inspection.	II Hazardous		

Oil Cooler Bearing FMEA → TBO Extension Major Hazard

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Failure Mode	Local Effect	Next Higher Level Effect	End Effect	Detection Method	Compensating Provisions	Failure Class	2500 TBO
Bearing failure	Oil cooler shaft bearings fail and become loose or seize	Contact between impeller and stator is possible.	Wear of fan blades possibly leading to failure of impeller. Loss of cooling air resulting in increased MGB oil temp.	Noise, vibration, and inspection	HUMS/BMU. Inspection. Blade containment test. Robust bearing cage design. Degraded mode testing to demonstrate filure is detectable before it becomes catastrophic.	III Major	X
Bearing cage fracture	Cage fracture causes loss of position and excessive wear of balls	In case of complete bearing failure, loss of blower shaft position. Possible bearing seizure.	Excessive oil cooler vibrations.	Noise, vibration monitoring.	HUMS/BMU. Inspections. Redundant component.	III Major	X
Bearing wear	Excessive wear of bearing balls and races results in increased bearing clearances	Increased bearing clearance / play accelerates wear	Excessive oil cooler vibrations.	Vibration.	HUMS/BMU. Inspections. Redundant component.	IV Minor	X
Ball sliding	sliding motion causes shearing between balls and cage/ring flange	Vibration	Excessive oil cooler vibrations.	Vibration	HUMS/BMU. Inspections. Redundant component.	IV Minor	X
Ball spall	Surface or subsurface crack or pitting propagates to delaminate material from bearin races or balls	Vibration. Increased play.	Excessive oil cooler vibrations.	Vibration.	HUMS/BMU. Inspections. Redundant component.	IV Minor	X

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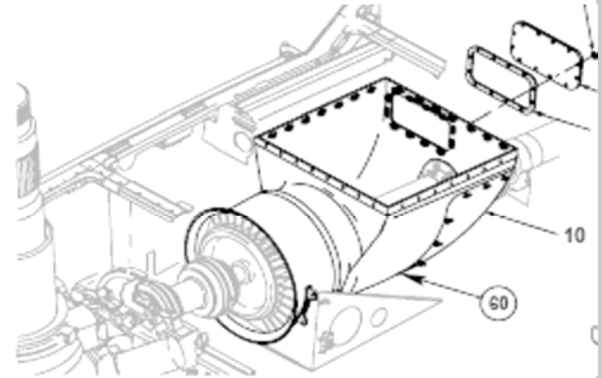
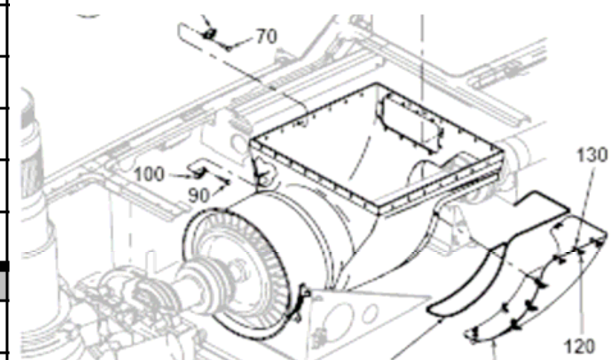
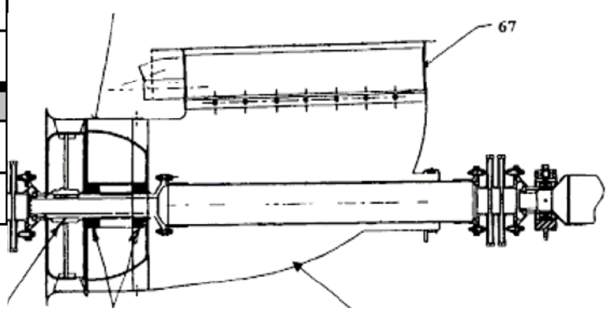
Oil Cooler Inspection Requirements: 50, 250, and 500 Hr

	Oil Cooler Related Inspections	Component Failure Mode	Failure Class
	50 Hr Inspection		
	4E. INSPECT OIL COOLER NO. 1 DRIVESHAFT COMPARTMENT:		
	(a) Open access doors and inspectvlatches, hinges, and door seal for obvious damage and security.		NA
	(b) Fuselage structure for obvious damage, cleanliness, and corrosion.	Non Oil Cooler	IV Minor
	(c) Tail rotor driveshaft and driveshaft couplings for obvious damage, loose hardware, and security.	Shaft	TBD
	(d) MGB oil cooler blower fan blades for damage and security. Inspect fan blades for evidence of contact between fan blades and housing.	Fan	III Major
	(e) Check fan rotor to ensure no rotational movement with rotor brake engaged.	Fan	III Major
	(f) Inspect visible area around fan. Inspect for signs of purging grease.	Bearing	IV Minor
	(g) Oil cooler support bracket for obvious damage.	Support Bracket	IV Minor
	(h) Fuel shut off valves, actuator rack and shut off valve electrical wiring for security.	Non Oil Cooler	NA
	(i) Pneumatic start lines, couplings, and shut off valves for security and integrity.	Non Oil Cooler	NA
	(j) Start control valve for security and integrity.	Non Oil Cooler	NA
	(k) Close oil cooler access doors and assure security of hinges and latches.		NA
	250 Hr Inspection		
	1. Main gear box oil cooler bearing for purged grease.	Bearing	IV Minor
	12. Inspect oil cooler driveshaft (inside duct) for damage, missing hardware and security.	Shaft	TBD
	13. Inspect visible area around fan and exit fan. Inspect for any signs of purging grease. Check for debris.	Fan	IV Minor
	500 Hr inspection		
	4. Inspect the oil cooler access duct for debris.	Fan/Duct	IV Minor
	5. Inspect the oil cooler blower fan blades for damage. Inspect bearing for evidence of purged grease.	Fan/Bearings	IV Minor

Directly Applicable **Indirectly Applicable** **N/A to Inspection**







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S-92 Fleet Opportunity –
Calibrate rig/aircraft condition indicators & thresholds

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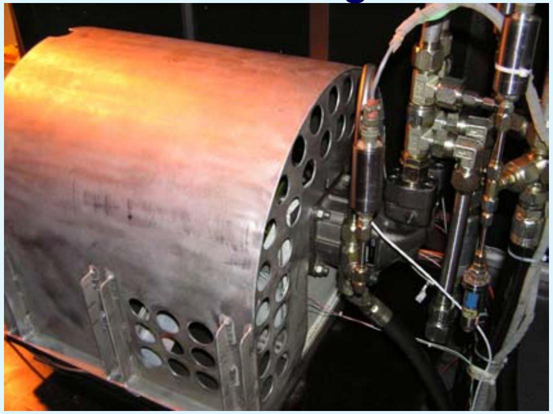
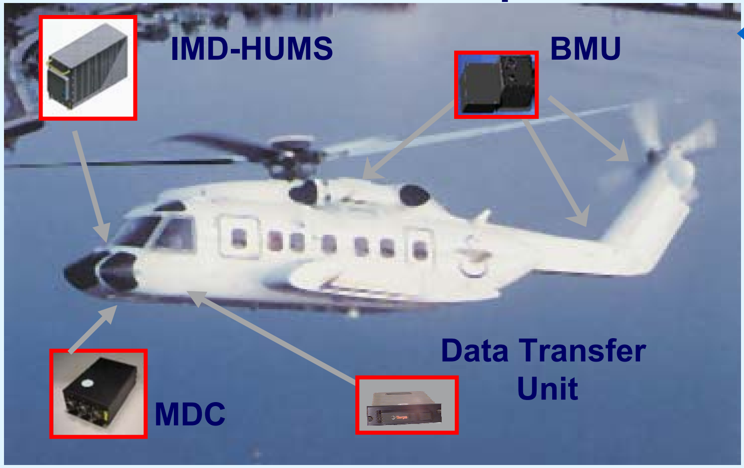
New Bearing

Oil Cooler Buildup

Oil Cooler Rig Test



S-92 HUMS Data Acquisition



High Time Bearings

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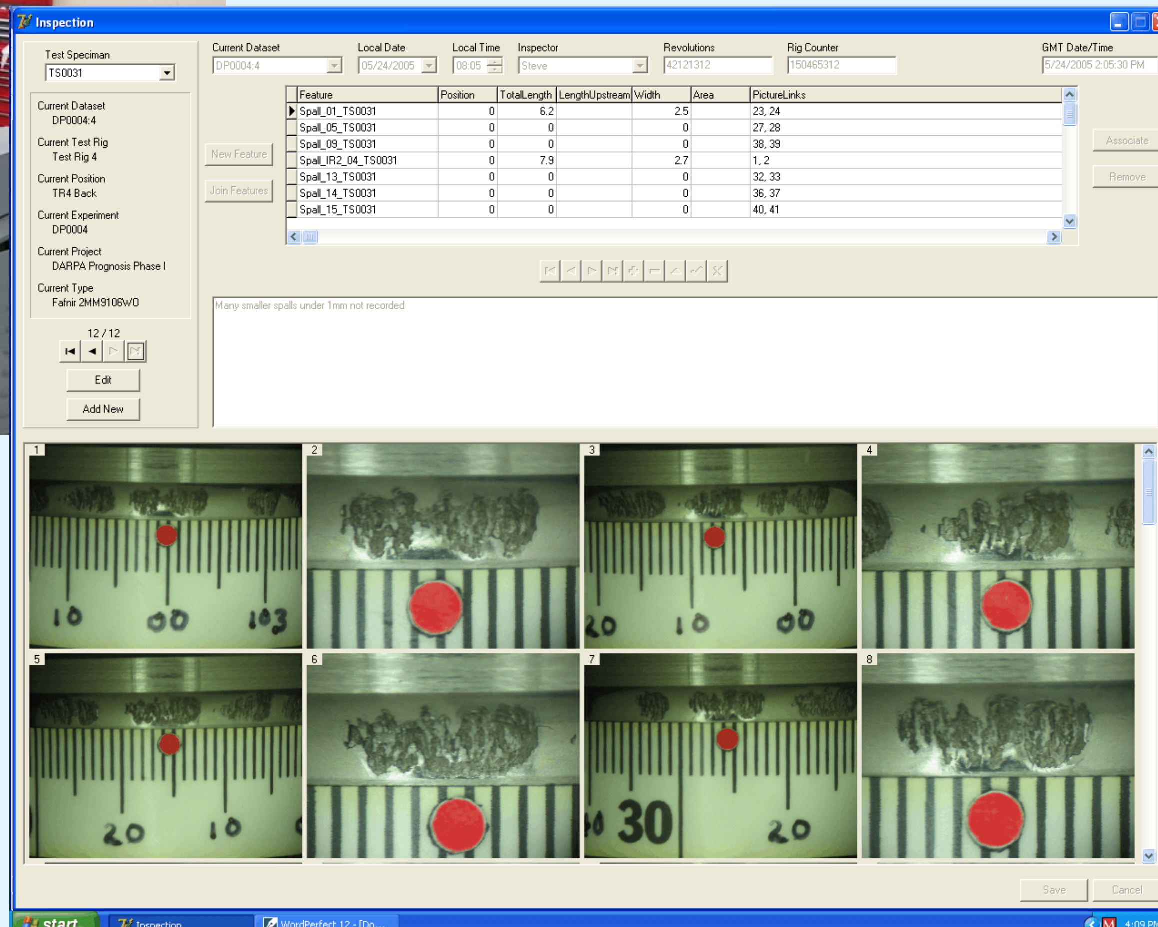
Bearing Bench-Top Tests – Understand failure progression & calibrate condition indicators



Courtesy of Sentient Corp.

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Supporting data requirements

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Priority	New Data Description	Intended Data Use
1	New oil cooler test stand data	Correlation of test stand data with HUMS data. To support of definition of HUMS thresholds from test stand data.
2	High-time oil cooler test stand data	Correlation of test stand data with HUMS data. To support of definition of HUMS thresholds from test stand data.
3	Bearing fault test	Validation of physics of failure and vibration features (if necessary)
	Bearing ball/race spall or wear	
	Bearing cage fault	
4	Oil cooler seeded fault tests of bearing fault(s)	Validation of HUMS fault detection capability.
	Bearing ball/race spall or wear	
	Bearing cage fault	
5	Long endurance bearing fault test (200 hr or failure)	Validation of failure progression rate and definition of thresholds (if necessary)
	Bearing ball/race spall or wear	
	Bearing cage fault	
6	Long endurance oil cooler seeded fault test (200 hr or failure)	Validation of failure progression rate and definition of thresholds.
	Bearing ball/race spall or wear	
	Bearing cage fault	
7	Oil cooler seeded fault test of other faults to support optional credit of modifying oil cooler inspection requirements	Validation of HUMS fault detection capability and vibration features

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Application of HUMS algorithms and methodologies

HUMS data analysis

There are three elements to the HUMS data analysis to be performed in support of the oil cooler CBM credit validation research:

1. A statistical analysis of the outputs from the current S-92 HUMS mechanical diagnostic algorithms from the in-service S-92 fleet

- The analysis will correlate the HUMS data with component condition and maintenance information, and also establish data variability across the operational fleet

2. The application of Smiths Aerospace's gear, shaft and bearing VHM techniques to data acquired from oil cooler testing

- Although there are detailed differences in the algorithms used by different HUMS suppliers, all the current major suppliers have adopted the similar approaches.

3. The application of Smiths' advanced HUMS data analysis methodologies to the oil cooler data

- The primary goal of applying such methodologies is to determine the impact they may have on the ability to achieve HUMS CBM credits.

Advanced HUMS data analysis methodologies

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Smiths is developing and trialling advanced HUMS data analysis methodologies on a UK CAA HUMS research program

- The goal is to further improve HUMS fault detection performance

A new HUMS anomaly detection capability has been developed

- The anomaly detection processing simplifies a complex data picture through an effective fusion of multiple HUMS condition indicators. This fusion emphasizes abnormal combined indicator trends and suppresses trends that are within normal ranges.
- A novel data modelling process was successfully developed to overcome the particular challenges of working with operational HUMS data subject to a range of unknown in-service influences.
- The new capability has been successfully demonstrated on a large database of historical HUMS data, and has successfully completed a 6 month in-service trial on Bristow Helicopters' European AS332L fleet.
- Several faults have been detected that were missed by the current HUMS.

Anomaly model outputs can be fused with other information in a higher level probabilistic reasoning layer

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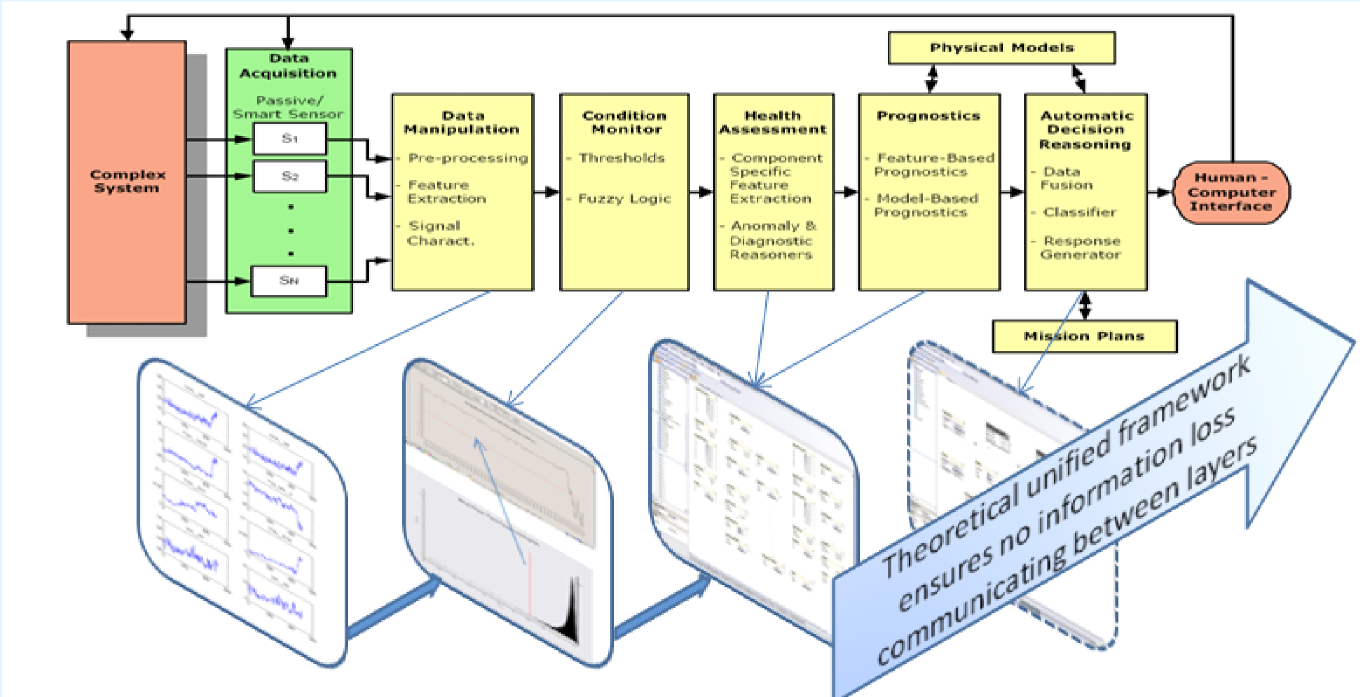
The advanced methodologies are based on Smiths' Probabilistic Diagnostic and Prognostic System (ProDAPS)

The figure shows how ProDAPS components sit within the OSA-CBM architecture (Open System Architecture for Condition Based Maintenance)



Signal processing to produce a set of condition indicators	Data Fusion and Anomaly Detection to recognise significant changes in state	Anomaly model embedded within reasoning network for fusion with high level information and other system components	Optional decision reasoning for automated action or decision support

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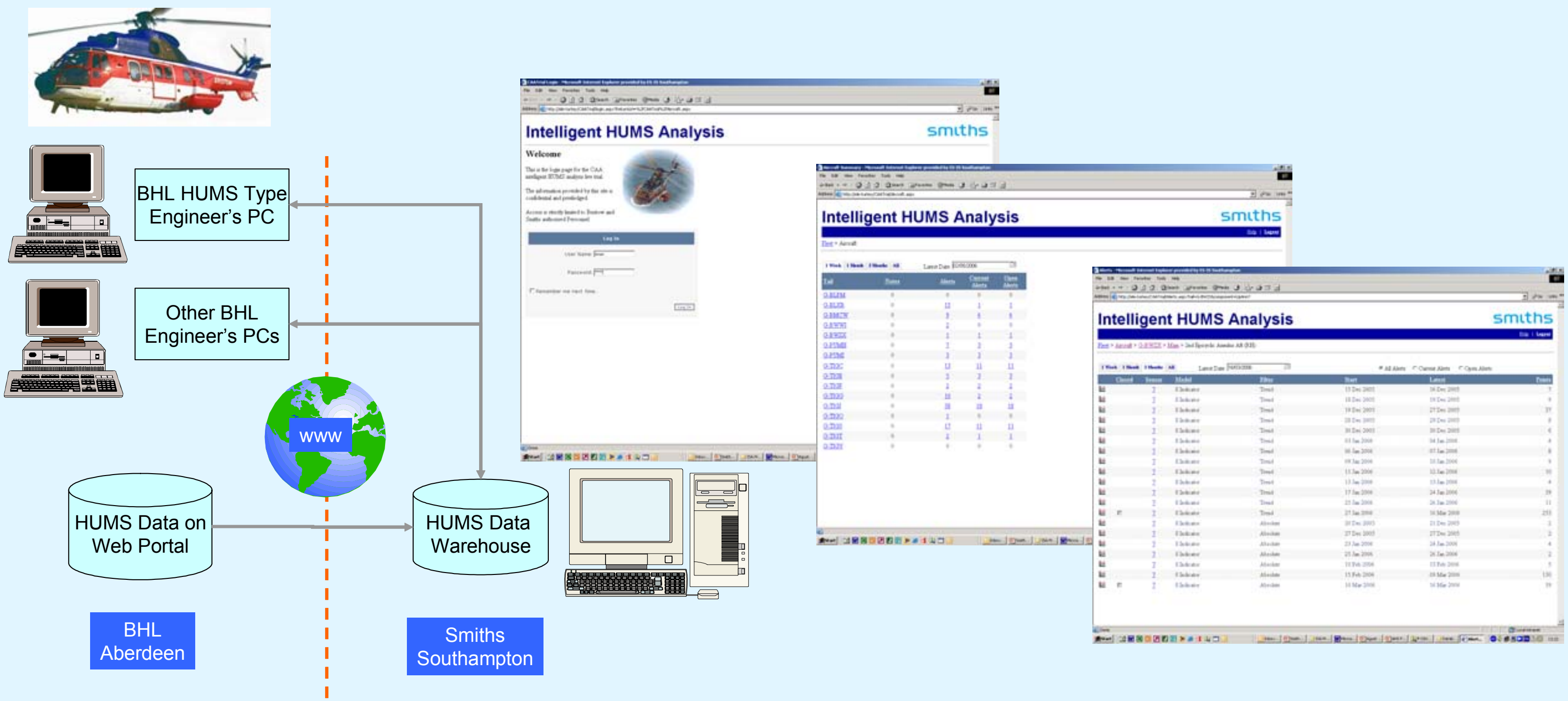
Web-based anomaly detection system for CAA trial

The anomaly detection system currently being trialled by Bristow Helicopters operates as a secure web server, located at Smiths in Southampton

- HUMS data automatically transferred overnight from Bristow's Web Portal
- Data automatically imported into the HUMS data warehouse and analysed
- Bristow have a remote secure login to the system to view results at any time



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End-to-end CBM credit approval process

Review of AC 29-2C MG-15

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AC 29-2C MG-15 states that:

- "The certification of HUMS must address the complete process, from the source of data to the intervention action. There are three basic aspects for certification of HUMS applications: Installation, Credit Validation, and Instructions for Continued Airworthiness (ICA)."

There will be a primary focus on credit validation, which includes the following items:

- Description of application and associated credit
- Understanding of the physics involved
- Validation methodology (direct & indirect evidence)
- Controlled introduction to service
- Continued airworthiness and synthesis of credit

All relevant requirements of the AC will be addressed, and these are shown on the following chart

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Chart showing the key requirements in AC 29-2C MG-15 that must be addressed in the awarding of a HUMS credit

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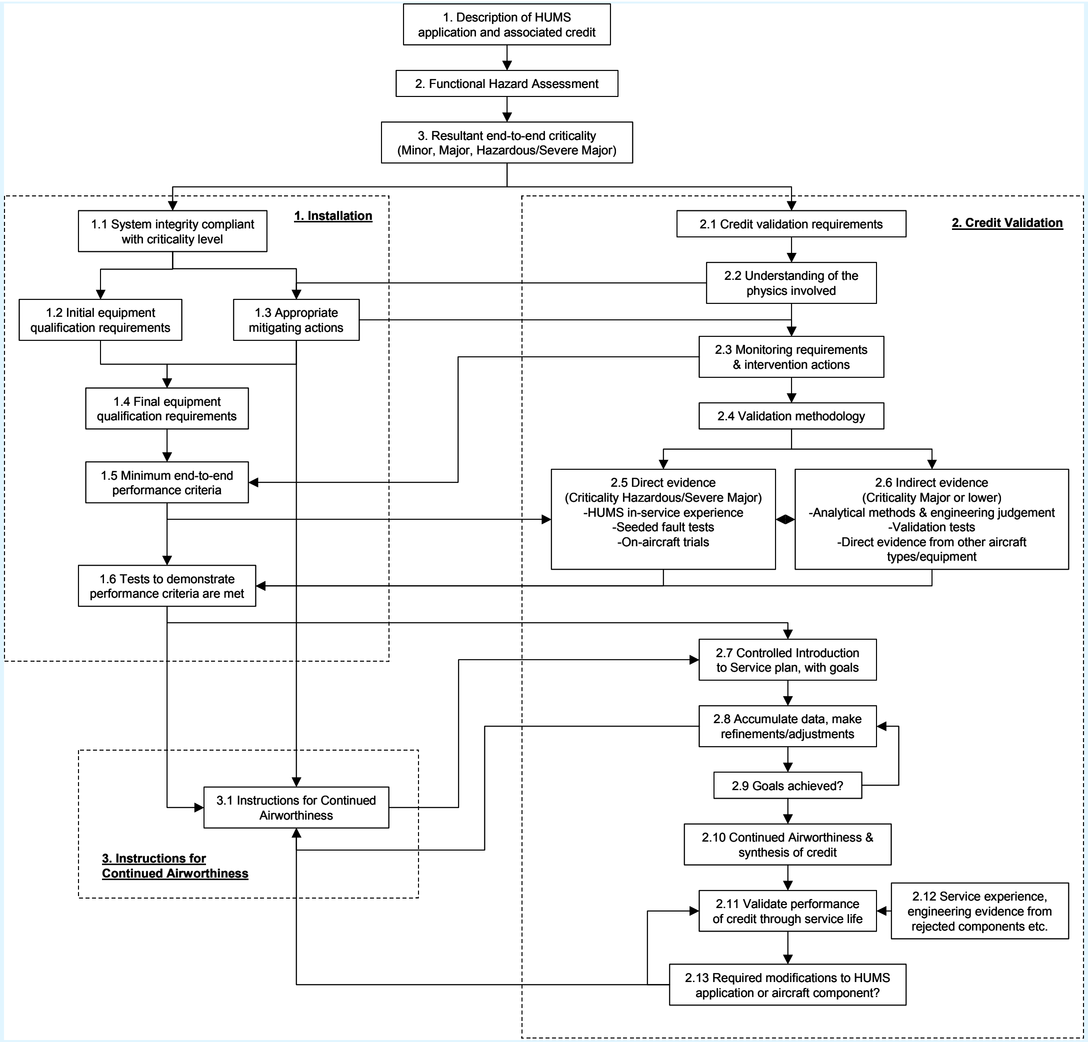

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Application of the AC to a particular CBM credit

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AC 29-2C MG-15 provides useful guidance material, and contains well-founded requirements

However, these are defined in generic terms, and potential issues to be addressed in applying the AC to the end-to-end process of achieving a particular CBM credit may include:

- Understanding the interactions between requirements in different sections of the document (i.e. Installation, Credit Validation, and ICA).
- Converting the generic guidance into specific plans for a defined HUMS application providing a CBM credit that are acceptable to a certifying authority.
- Determining the cost effectiveness and appropriate timing of any CBM credit application.
  - For example, conducting a series of seeded fault tests to provide direct evidence to validate a credit can be expensive. However, after a number of years of HUMS operations, much of the required direct evidence may have been accumulated from the in-service experience at little cost.
  - It is important HUMS experience is properly documented and reviewed.

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Program status and Summary

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Program Status – To Date

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Budget/Expenditure

- 26% spent of the total award.

Schedule

- Estimated 3 month slip in schedule

Issues/Concerns

- Slow start up caused delay in first deliverable, but overall five-year program should remain on schedule

Accomplishments

- Completed Task 2

Deliverables

- Completed the first annual technical report, including the Task 2 deliverables:
  - 0003a – Failure and hazard assessment report on selected component and aircraft
  - 0003b – Summary report documenting the development of CBM credit, requirements, and risks

Program Status – Near Term Plans

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There will be some flexibility in the scheduling of tasks to aid efficiency and to make allowance for the timing of the availability of different data sets. The following near term activities are anticipated:

Task 3

- SAC are preparing to ship a first batch of S-92 oil cooler HUMS data to Smiths, together with supporting maintenance information.
- Smiths will then create a database for this, and commence data exploration and analysis.

Task 4

- SAC are about to complete the prioritized oil cooler test plan, and to ship a batch of existing H-60 oil cooler test data to Smiths
- SAC will then commence oil cooler testing in accordance with the plan

Task 5

- Smiths will commence analysing the data shipped by SAC in Task 4

Task 6

- An oil cooler credit validation plan will be developed

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Summary

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A well-targeted HUMS research program has been defined

- This will validate the application of AC 29-2C to an example CBM credit.
- It will also support the on-going development of the CBM credit potential of HUMS mechanical diagnostics functions.

Task 2 has been completed

- An analysis of the generic credit potential of HUMS has been performed.
- The S-92 oil cooler has been selected as the target component for the research.
- The target CBM credit has been defined as elimination of the current 2,500 hr oil cooler TBO, plus optionally the elimination of some inspections.
- The highest level of criticality of this credit has been identified as “Major”.
- The applicable HUMS algorithms and methodologies have been defined.
- An analysis of the requirements of AC 29-2C has been performed.

Work will now focus on the acquisition and analysis of S-92 HUMS data and oil cooler test data for credit validation

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Thank you for your attention

Questions?

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